METEOROID STRUCTURE: CURRENT VIEWS, ASTROPHYSICAL IMPORTANCE AND SOFIA POSSIBILITIES

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ABSTRACT

While recent meteor electro-optical observations and theoretical ablation models have provided clues to the structure of meteoroids and the role of volatile, possibly organic, materials in meteors, many questions remained unanswered. An airborne platform, in conjunction with ground based observations, offers promise for resolution of some of the key questions about meteoroid structure, and ultimately will contribute to questions about astrophysical origins and space operations hazards from natural meteoroids.

INTRODUCTION

After decades of intensive work by numerous researchers, a definitive view of the structure and composition of meteoroids, and the mode of atmospheric ablation of these objects, remains elusive. There is general support for the idea that many cometary meteoroids have some sort of dustball structure in which a meteoroid is actually a collection of at least hundreds to thousands of small constituent grains (Jacchia 1955; Verniani 1969; Hawkes and Jones 1975; Fisher et al. 2000). Hawkes and Jones (1975) proposed a quantitative dustball model in which these constituent grains were bound by a more volatile second component. This proposed meteoroid structure is, in broad features at least, consistent with models of organic coated silicate interstellar and cometary grains proposed by Greenberg and others, and also consistent with the Halley dust observations of significant CHON composition. According to this model what we call a single meteor event may be a cluster of fundamental grains which have been released prior to intensive ablation (following loss of the volatile component high in the atmosphere), or one experience simultaneous grain release and intensive grain, Several authors have shown that the quantitative dustball model matches meteor observations (see e.g. Beech 1984). More recently Borovicka et al. (1999) have proposed a modification of the model in which Na plays a key role as the more volatile constituent. If a sufficiently detailed picture of the composition and physical structure of these dustball meteoroids can be affirmed (e.g. the mass distribution of the constituent grains; the fraction of the original material was volatile; the degree of variability from meteoroid stream to meteoroid stream), then this will help to constrain models of solar system formation. The importance of delivery of organic material to the primitive and current Earth is also dependent on these issues (e.g. Jenniskens et al. 2000). Understanding meteor fragmentation and ablation processes is key to dealing with selection biases inherent in radar meteor detection (e.g. Campbell and Jones 2003). Furthermore, a clear understanding of the physical structure and ablation mode is key to a complete understanding of the potential hazards to space operations posed by natural meteoroids.

METEOROID FRAGMENTATION OVERVIEW

Several models of potential meteoroid structure and fragmentation have been proposed. One possibility is a compact, high strength structure (similar to chondritic stony meteorites) which fragments into a relatively small number of discrete pieces due to some combination of thermal and aerodynamic stresses.

The Peekskill meteorite fireball graphically demonstrates this mechanism (Brown et al. 1994) which is common for bright meteors but extremely rare in the small meteoroids studied with image intensified video techniques. A second mode of fragmentation is some spraying of droplets from a molten surface level of the meteoroid during atmospheric entry. A third possibility is that the meteor will fragment into smaller and smaller pieces during atmospheric flight in response to steadily growing dynamic pressures. A fourth possibility is continuous fragmentation through dispersal of many small grains during the atmospheric flight, and Babadzhanov (2002) argues that this is the dominant mode of fragmentation at least in the size range studied using photographic techniques. A fifth possibility is that the meteoroid is already fragmented into a collection of constituent grains prior to atmospheric entry. Of course combinations of these models are possible, for example a dustball meteor which has one or more episodes of fragmentation into large number of grains (and subsequent flare production) as well as continual release of smaller numbers of grains. In the remaining portions of this paper we will overview some of the questions related to meteoroid structure and meteor ablation which are particularly suited to contributions from SOFIA.

ARE METEOR LIGHT CURVES SMOOTH?

Perhaps the most obvious way to search for evidence of a dustball structure and fragmentation is to look for short scale irregularities on meteor light curves resulting from changes in ablation rate and surface area due to in-flight fragmentation. Jiang and Hu (2001) claim several detections demonstrating this effect and consistent with the Hawkes and Jones (1975) dustball model of meteoroid structure. Hawkes et al. (2001) proposed some techniques for doing this and reported on some tentative early results. However, the combination of readout noise in the CCD, scintillation due to the atmosphere, image intensifier noise, and short temporal scale skyglow variations make it very difficult to isolate true short term fluctuations, With SOFIA two of these effects (atmospheric scintillations and skyglow temporal variations) will be significantly reduced. Providing the stability of the observing platform will not be an issue, this could offer the best promise for studying light curve variability. Two low noise image intensified CCD detectors with moderate to high spatial resolution should be employed in coincidence mode for this study.

IS METEOR WAKE DUE TO DIFFERENTIAL DECELERATION COMMON?

Meteor wake can be caused by long duration photochemical processes and by differential deceleration of grains with different physical characteristics so that light is simultaneously produced from a distributed spatial region. It has been difficult to obtain many clear examples of this with three previous studies of wake in faint meteors each providing only a few examples (Robertson and Hawkes 1992; Shadbolt and Hawkes 1992; Fisher et al. 2000). To have success in this it will be necessary to improve spatial and temporal resolution, while also reducing noise. Again, the reductions in scintillation and the darkening of the unresolved sky background may make SOFIA a good platform for this, particularly if it is possible to use gated image intensifier technology connected to high spatial resolution optics (Hawkes et al. 2004).

WHAT IS THE NATURE OF THE ORGANIC VOLATILE COMPONENT OF METEOROIDS?

Perhaps the most fundamental question is the nature and amount of the volatile component of the quantitative dustball structure (Hawkes and Jones 1975). SOFIA offers the opportunity to extend the spectral range which can be observed, which may offer opportunities to clearly identify the products of the organic components of meteoroids. This topic is covered in detail in this proceedings by Trigo-Rodriguez (2004), and in the article by Jenniskens et al. (2000).

WHAT IS THE MASS DISTRIBUTION OF THE FUNDAMENTAL GRAINS FROM WHICH COMETS FORMED?

Meteor flares can be used to estimate the mass distribution of simultaneously released dustball grains (see e.g. Hawkes et al. 2002 and references therein). Unfortunately these are rare events for any single detectors. As Jenniskens et al. (2004) point out, the meteor rate from an airborne platform can be significantly enhanced by looking at very low elevations not possible for terrestrial observations. The Leonid airborne missions clearly proved this point.

CAN SPATIALLY SEPARATED GRAIN CLUSTERS BE OBSERVED?

There are several reported cases of clearly separated but clustered meteors (e.g. Watanabe et al. 2003). The study of these rare events could be enhanced from SOFIA due to darker backgrounds, and the possibility of looking at low elevation angles for a larger collecting area. Reduced scintillations from the SOFIA platform may assist with detection of dual or multiple fragment simultaneous meteors.

IS ATOMIC SPUTTERING IMPORTANT IN METEOR ABLATION?

Until very recently it has been assumed that the amount of ablation is very low until the meteor reaches temperatures where intensive vaporization occurs. However, Coulson and Wikckramasinghe (2003) and Rogers et al. (2004) have shown that in at least some mass/velocity regimes sputtering processes should be considered. Direct experimental verification of this sputtering will probably need to come from observation of a low luminosity, high altitude early part of meteor light curves. This is very challenging observationally, and it may be difficult to resolve high altitude ablation of a volatile component (see e.g. Campbell et al. 2000) from sputtering.. Reduced skyglow and less scintillations may assist with the effort from the SOFIA platform. The high altitude meteors reported by Fujiwara et al. (1998), Spurny et al. (2000) and Koten et al. (2001) may be able to be explained by this process.

DISCUSSION

SOFIA Upper Deck offers excellent opportunities for electro-optical meteor observations, and the potential to definitively answer key questions about the structure and atmospheric ablation of meteoroids. In turn these will allow us to answer questions about our origins, in particular the dust conditions in the primitive solar system and the importance of delivery mechanisms of organic material to Earth through meteoroid ablation. The features and frequency of clustered dustball meteoroids are important for evaluating the hazards to space operations from meteoroid impacts.

Several key advantages of the SOFIA Upper Deck platform over ground based meteor observations are briefly summarized below.

- The spectral region which can be observed is expanded, in particular into the infrared where organic volatile components may be detected.
- The Airborne Leonid missions have illustrated that the enhanced collection area offered by low altitude pointing directions, only possible from airborne and space detectors, lead to significantly higher meteor rates. This allows more efficient collection of rare observational data such as clustered meteoroids, flare events, and spectra from a wider sampling of cometary meteoroids.
- The reduced atmospheric scintillation (and to a lesser degree the reduced unresolved skyglow background) offer the opportunity to search for slight irregularities on light curves as indicators of fragmenting dustballs.

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